A NEW INSTRUMENTAL WAY TO MEASURE SNOWFALL SWE IN MOUNTAIN AND POLAR CATCHMENTS DIRECTLY, ON THE KILOMETER-SCALE AND IN NEAR REAL TIME

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ABSTRACT

The Snow Water Equivalent (SWE) of snowfall is important but difficult to measure. While numerous techniques have been developed, measurements are still too sparse, too poorly distributed, too infrequent, too biased and too small to represent the variability of SWE in mountain landscapes. Snow pillows, pluviometers and other instruments have not solved this problem: precipitation products have large biases over mountain ranges worldwide. A novel measurement technique can now provide direct observations of snowfall SWE in polar and alpine settings accurately and on far larger spatial scales than most existing in situ methods, over areas comparable to model and satellite resolutions. By sensing water-pressure changes in lakes it is directly sensitive to the mass of new snowfall over the whole area of the lake, rather than a proxy for mass or a measurement at a point, and it is capable of high-frequency, high-resolution, low-cost and low-bias SWE measurements that do not saturate over time. Tests of this technique show it to be highly sensitive to falling snow, and highlight the sometimes-large errors present in conventional instruments, precipitation models and products. (Keywords: SWE, snowfall, lake, water, pressure).

INTRODUCTION

In a drought, water from the seasonal snowpack in the mountains of the western United States is worth up to $88 billion per year (Sturm et al., 2017) but there remain poorly-known but large biases in even multi-decadal climatologies of precipitation in the mountain cryosphere, particularly in winter (Figure 1). These gridded precipitation products are interpolated from field measurements, primarily from automated pluviometers and snow pillows, which are also used to calibrate and validate weather and climate models. The large biases shown in the precipitation products therefore point to important weaknesses in the instrument array, particularly regarding mountain snowfall.

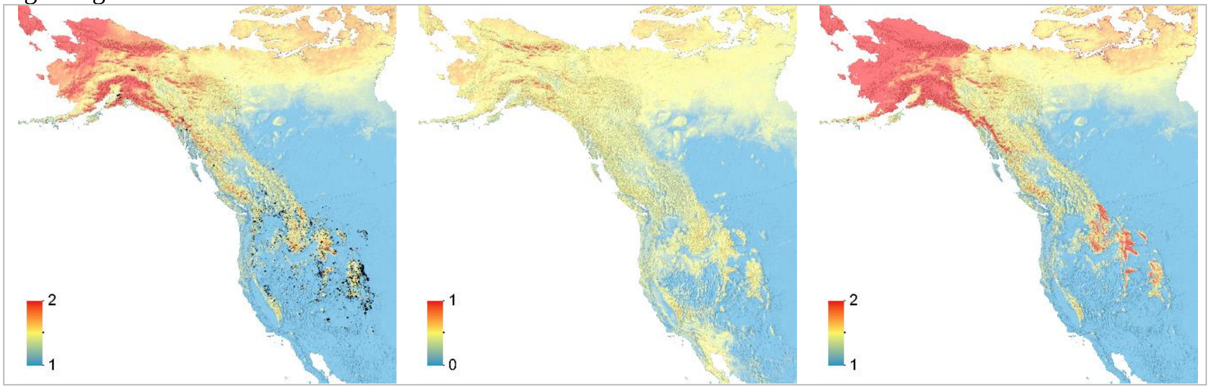

Figure 1. **a)** Bias-correction factor (blue-to-red scale, after Beck et al. (2020)) required for the observation-based WorldClim v2 (Fick & Hijmans, 2017) climatological annual precipitation product to agree with catchment hydrology in western North America. Similar factors are required for the CHELSA v1.2 (Karger, 2017) and CHPclim v1 (Funk et al., 2015) climatologies (not shown). GHCN weather stations (Menne et al., 2012) are indicated by black crosses within the 'mountain cryosphere', i.e., mountain areas (Karagulle et al., 2017) where the January mean temperature is below freezing (Fick & Hijmans, 2017); **b)** Uncertainty in the annual bias correction (upper minus lower bound of factor estimate); **c)** Bias-correction factor for January.

Weaknesses in the instrument array stem from instrumental bias and limited spatial sampling of snow in the landscape. Well-known instrumental low-biases of up to 90% affect pluviometers in windy conditions, and snow pillows experience low biases due to ice-layer bridging, or high biases of 40-200% due to the effect of the pillow on snow melting (e.g., Beck et al., 2020; Burgess et al., 2010; Johnson & Marks, 2004; WMO, 1998). Other snowfall and snowpack sensors (e.g., scales, lysimeters, totalisers, gamma radiometers, electrical impedance sensors, GPS receivers, cosmic-ray neutron sensors, geolysimeters) suffer from measurement, cost and maintenance limitations, contributing to a sensor array that is prone to inaccuracy and is often poorly distributed and sparse relative to snowfall variability (summarised in Pritchard et al., 2021). Furthermore, with

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the exception of the geolysimeter method (Smith et al., 2017), these sensors have footprints spanning typically 0.1-100 m, far smaller than the kilometers-scale of individual grid cells in the models and products based upon them and tested against them. The scaling errors from this mismatch have led to SWE biases of up to 200% even in the vicinity of the instruments (Molotch & Bales, 2005).

DESCRIPTION OF THE NEW METHOD

A new instrumental method helps overcome the fundamental limitations in accuracy and spatial scale of existing snowfall and snowpack instruments (Pritchard et al., 2021). Like a snow pillow, this method measures the change in mass of an accumulating snowpack (primarily from new snowfall) as a pressure change, but rather than measuring the fluid pressure in a small, sealed bladder it uses changes in the water pressure observed at the bed of a natural lake. In open lake systems, water levels (i.e., pressure) can change due, for example, to drainage into or out of the lake as well as any new mass supplied by precipitation. In winter though, when the lake catchment is frozen and surface runoff stops, pressure changes due to drainage exhibit slow trends that can be removed to isolate the winter snowfall signal. Figure 2a shows a water-pressure time series from a Finnish arctic lake, with a declining trend due to ongoing net winter lake drainage (black line from e.g., 23/03 to 02/04/2018) punctuated by a series of pressure jumps due to snowfall onto the frozen lake surface (e.g., on 06/04/2018) that were also detected by a nearby pluviometer (blue dots). Subtraction of the drainage trend reveals the mass (i.e., SWE) of new snow accumulated in each event (Figure 2b) which, because the lake is in hydrostatic equilibrium, represents the mean over the 10.95 km^2 lake surface. The lake is 274 million times larger than the pluviometer aperture (0.04 m^2) (Pritchard et al., 2021) and the 06/04/2018 snowfall signal equates to 160,000 tons of water measured by the water-pressure sensor, versus 0.0006 tons by the pluviometer.

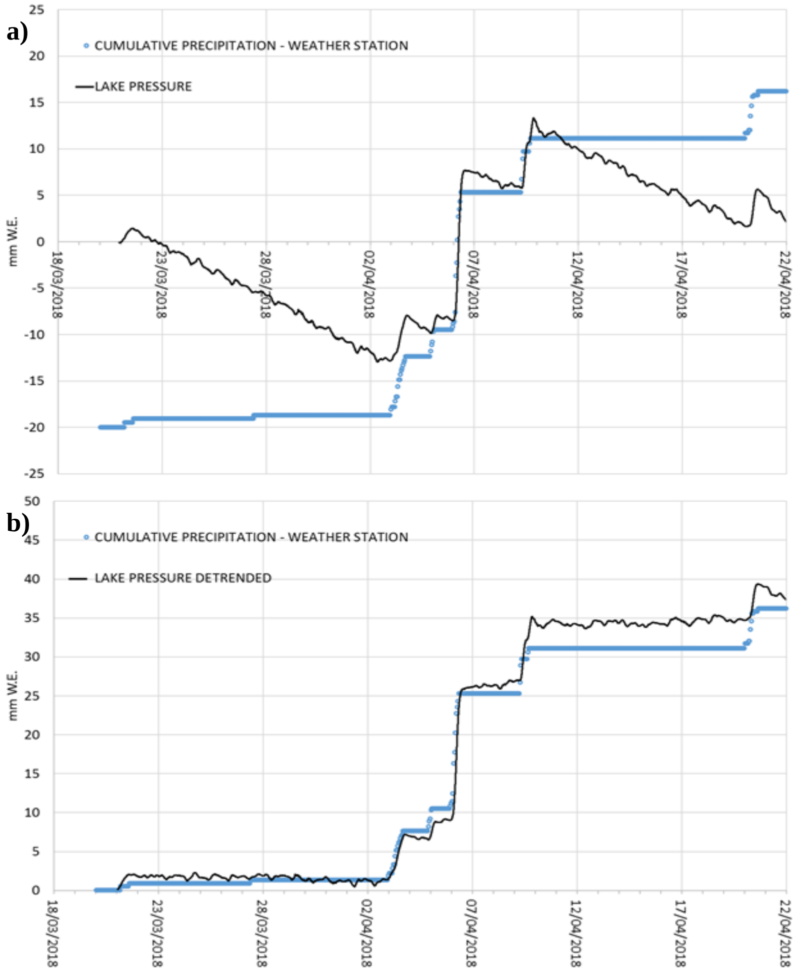

Figure 2. **a)** Water pressure time series for March-April 2018 from Lake Orajärvi, Finland (black line) and cumulative precipitation from the double-fence inter-comparison reference pluviometer of the Finnish Meteorological Institute at Sodankylä (WIGOS-ID 0-20000-0-02836, 7 km from Orajärvi) (shifted by -20 mm W.E. for display). **b)** As above, with detrended water pressure (after Pritchard et al., 2021).

This lake method avoids major instrumental biases inherent to other methods: the submerged water-pressure sensors do not interfere with snowfall or melting so avoid the turbulence-driven undercatch, wetting losses, evaporation, snow-capping and slumping of a pluviometer, or the instrument-induced melt effects of snow pillows. For all lakes wider than a few meters, the limited flexural strength of a lake-ice layer also means that the bridging biases experienced by snow pillows are avoided. The large dynamic range of the pressure sensors (e.g., 10 m W.E.) far exceed the signal-saturation limits of, for example, the Campbell CS725 gamma radiometer (~0.60 m W.E., Campbell (2020)) or the Hydroinnova neutron radiometer (~0.15 m W.E., Hydroinnova (2020)), and the direct relationship between observed pressure change and snowfall SWE avoids the calibration uncertainties of these radiometers and other indirect SWE sensors. Most strikingly, the far larger observable areas of lakes (e.g., eight orders of magnitude larger in the above example), greatly improves the representation of snowfall SWE in the landscape, and can span areas on the grid-scale of precipitation products and weather models, largely eliminating scaling biases and uncertainties of point-to-grid interpolation, calibration and validation. Finally, pressure-sensors and associated equipment are readily available, field-proven, low-maintenance, low-power, lightweight, easily-deployed technology, costing ~30% of the installed cost of a snow pillow and <20% of a Campbell CS725 (Pritchard et al., 2021). Potentially thousands of such radiometers with their ~80 m^2 footprints would be needed for a representative sample of SWE over an area comparable to Lake Orajärvi, costing hundreds of millions of dollars (Stranden et al., 2015), in contrast to the single pressure sensor deployed here in under an hour at a cost <$5000.

APPLICATION OF THE METHOD

Accuracy and Precision

The uncertainty of the pressure sensors used here (their instrumental imprecision) is measurable and small (e.g., ±0.02 mm at two standard errors). The relative instrumental accuracy over the relevant timescales is high, and in practice instrumental drift is removed during this method's drainage-detrending process (Pritchard et al., 2021). The accuracy of measured water pressure change is occasionally prone to transient bias (on hourly timescales) due to local wind effects on pressure, but these can be identified from the observations, do not propagate through cumulative snowfall totals, and can be reduced by averaging of more than one pressure time series (Pritchard et al., 2021). Changes in SWE measured by this method are otherwise largely unbiased. The pressure signal is additionally sensitive to non-snowfall changes in snowpack SWE on a frozen lake surface due, for example, to wind transport and sublimation, but these are real SWE signals rather than measurement biases. The total SWE-measurement uncertainty (imprecision) is dominated by uncertainty in the drainage trend, and the trend and its uncertainty are quantifiable from the observed pressure in the pre- and post-snowfall periods. Total uncertainty across a snowfall event (typically ~12 hours) was estimated as ±1 mm W.E., or an average of ±3% of snowfall through each of 25 events in the Swiss Alps, a precision similar to or better than established methods (Pritchard et al., 2021). This combination of low measurement-bias and quantifiable precision is rare among snow instruments

Testing Of Gridded Products

The large area, absence of bias and high temporal frequency of lake measurements permit direct testing of gridded weather products. Figure 3 shows cumulative snowfall on a Swiss lake in March 2019, measured by the lake method (dP SWE), an adjacent MeteoSwiss pluviometer (AWS), the mean of 14 grid cells overlapping the lake from the gauge-and-radar observational precipitation product CombiPrecip, and the mean of 6 such cells of the Alpine numerical weather forecast model COSMO-1. Note that these other methods do not report their uncertainties, but this test reveals cumulative biases for this event of -29% for CombiPrecip and -62% for COSMO-1. The AWS reported a -13% lower snowfall but it is unknown whether this is due to instrumental undercatch or a real difference in snowfall between the point-scale (0.05 m^2) of the pluviometer and the 4.12 km^2 area of the lake observed by the other methods (Pritchard et al., 2021). A rigorous assessment of the gridded products would require observations of multiple snowfalls under different synoptic weather conditions, but this example demonstrates both the need and the potential for such an assessment using the lake method.

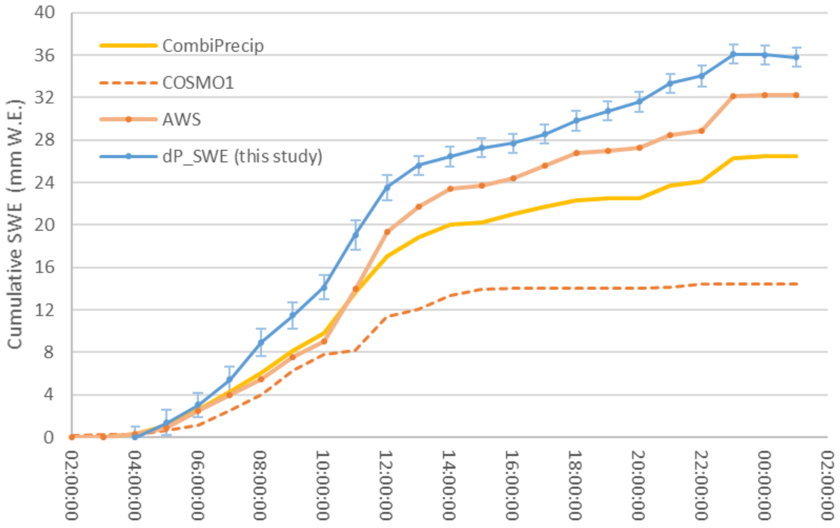

Figure 3. Cumulative snowfall SWE, Lake Sils, Switzerland, from 02:00 on 6 March 2019, from lake measurements (dP_SWE), a weather station (AWS), COSMO1 and CombiPrecip (from Pritchard et al., 2021).

CONCLUSION

The array of operational snow instruments in the world's mountain cryosphere does not adequately represent snowfall, leading to large low-biases in estimates of mountain precipitation. This is because most instruments are inherently prone to measurement bias and because they are too few, too poorly distributed and too small to sample snowfall in the landscape. A new method based on measuring changes in lake water pressure overcomes some of the major measurement biases of existing instruments, and their major sampling problem of measurement scale relative to the resolution of precipitation products and models. Furthermore, the lake-measurement system requires only mature, simple, autonomous, robust, low-power, lightweight and low-cost equipment in the field. This method does need lakes, but these are widespread in most ranges: there are, for example, over 25,000 lakes covering 1150 km^2 in the mountain cryosphere of the contiguous United States (USGS National Hydrography Dataset). Together, the advantages of this new method allow for snowfall to be monitored over a far larger fraction of the landscape than it is today.

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